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MILLIHERTZ OSCILLATION FREQUENCY DRIFT PREDICTS THE OCCURRENCE OF TYPE I X-RAY BURSTS

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ABSTRACT

Millihertz quasi-periodic oscillations reported in three neutron-star low mass X-ray binaries have been suggested to be a mode of marginally stable nuclear burning on the neutron star surface. In this Letter, we show that close to the transition between the island and the banana state, 4U 1636–53 shows mHz QPOs whose frequency systematically decreases with time until the oscillations disappear and a Type I X-ray burst occurs. There is a strong correlation between the QPO frequency ν and the occurrence of X-ray bursts: when $\nu \gtrsim 9$ mHz no bursts occur, while $\nu \lesssim 9$ mHz does allow the occurrence of bursts. The mHz QPO frequency constitutes the first identified observable that can be used to predict the occurrence of X-ray bursts. If a systematic frequency drift occurs, then a burst happens within a few kilo-seconds after ν drops below 9 mHz. This observational result confirms that the mHz QPO phenomenon is intimately related with the processes that lead to a thermonuclear burst.

Subject headings: X-rays: bursts, X-rays: individual (4U 1636–53, 4U 1608-52, Aql X-1)

1. INTRODUCTION

Revnivtsev et al. (2001) discovered a new class of low frequency quasi-periodic oscillation (QPO) in three neutron star X-ray binary sources (Aql X-1, 4U 1608–52 and 4U 1636–53). This new QPO has frequencies between 7 and 9 $\times 10^{-3}$ Hz, i.e. it is in the milli-Hertz range, and its other properties also differ from those of the other QPOs found in the neutron star systems (e.g. energy dependence, see van der Klis 2006). Although Revnivtsev et al. (2001) could not discard an interpretation related with disk instabilities, they concluded that the mHz QPO is likely due to a special mode of nuclear burning on the neutron star surface. This interpretation was strengthened by the results of Yu & van der Klis (2002), who showed that the kHz QPO frequency is anti-correlated with the luminosity variations during the mHz oscillation, suggesting that the inner edge of the disk slightly moves outward as the luminosity increases during each mHz cycle due to stresses generated by radiation coming from the the neutron star surface. This is contrary to the correlation observed between X-ray luminosity (L_x) and kHz QPO frequency, where the inner disk edge is thought to move in, as the accretion rate and hence L_x, increases (van der Klis 2006, and references within).

The properties of the mHz QPOs as observed up to now can be summarized as follows: *(1)* the fractional rms amplitude strongly decreases with energy, from ≈ 2% at 2.5 keV, down to an almost undetectable < 0.2% at ≈ 5 keV; *(2)* mHz QPOs occur only in a particular range of X-ray luminosity: $L_{2-20\ keV} \approx 5-11\times10^{36}$ erg/s; *(3)* the frequency of the mHz QPOs is between 7 and 9 mHz; *(4)* the mHz QPOs disappear with the occurrence of a type I X-ray burst; *(5)* as noted above, the kHz QPO frequency is approximately anti-correlated with the $2-5$ keV count rate variations that constitute the mHz oscillation.

Heger et al. (2007) suggested that the mHz QPOs could be explained as the consequence of marginally stable nuclear burning on the neutron star surface. They found an oscillatory mode of burning, with a period P_{osc} close to the geometric mean of the thermal[3] and accretion[4] timescales of the burning layer. For typical parameters, $P_{osc} \equiv \sqrt{t_{thermal} \cdot t_{accr}} \approx 2$ minutes, in accordance with the characteristic frequency of the mHz QPOs. The burning is oscillatory only close to the boundary between stable burning and unstable burning (in Type I X-ray bursts), explaining the observation that the mHz QPOs were seen within a narrow range of luminosities.

Two of the three sources in which Revnivtsev et al. (2001) found the mHz QPOs are transient atoll sources (Aql X-1 and 4U 1608–52) while the third one, 4U 1636–53, is a persistent atoll source (Hasinger & van der Klis 1989). The object of our current study, 4U 1636–53, has an orbital period of ≈ 3.8 hours (van Paradijs et al. 1990) and a companion star with a mass of ≈ 0.4 $M_\odot$ (assuming a NS of 1.4 $M_\odot$; Giles et al. 2002). 4U 1636–53 is an X-ray burst source (Hoffman et al. 1977) showing asymptotic burst oscillation frequencies of ≈ 581 Hz (Zhang et al. 1997; Strohmayer & Markwardt 2002). The aperiodic timing behavior of 4U 1636–53 has been studied with the EXOSAT Medium Energy instrument (Prins & van der Klis 1997) and with the Rossi X-ray Timing Explorer (RXTE, e.g. Wijnands et al. 1997; Di Salvo et al. 2003; Altamirano et al. 2007).

4U 1636-53 is a reference source for studying nuclear burning on the surface of a neutron star since it shows the full range of burst behavior: single and multi-peaked

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[3] The thermal timescale is defined as $t_{thermal} = c_p T/\epsilon$ where c_p, T and ϵ are the heat capacity at constant pressure , the temperature and the nuclear energy generation rate, respectively

[4] The accretion timescale is defined as $t_{accr} = y/\dot{m}$ where y and $\dot{m}$ are the column depth of the burning layer and local accretion rate, respectively.

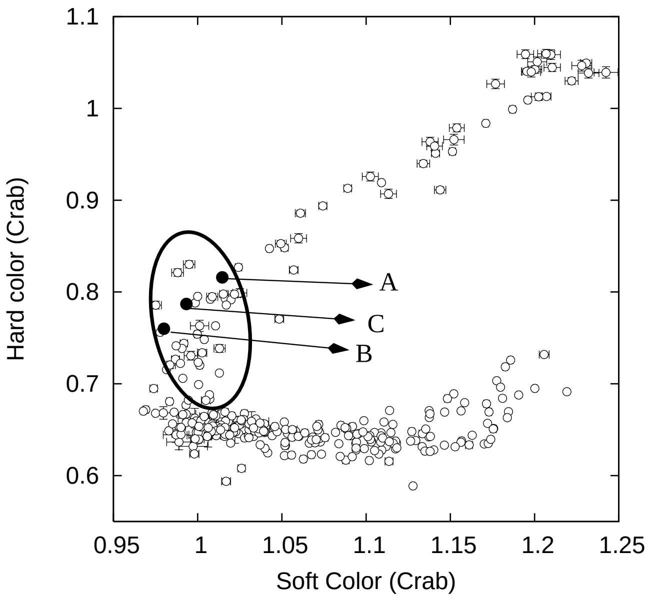

FIG. 1.— Color-color diagram as Altamirano et al. (2007). Each data point represents the average of an observation (≈ 2 to ≈ 30 ksec). The ellipse marks the region in which mHz QPOs with decreasing frequency were found. The labels A, B and C correspond to those in Figure 3.

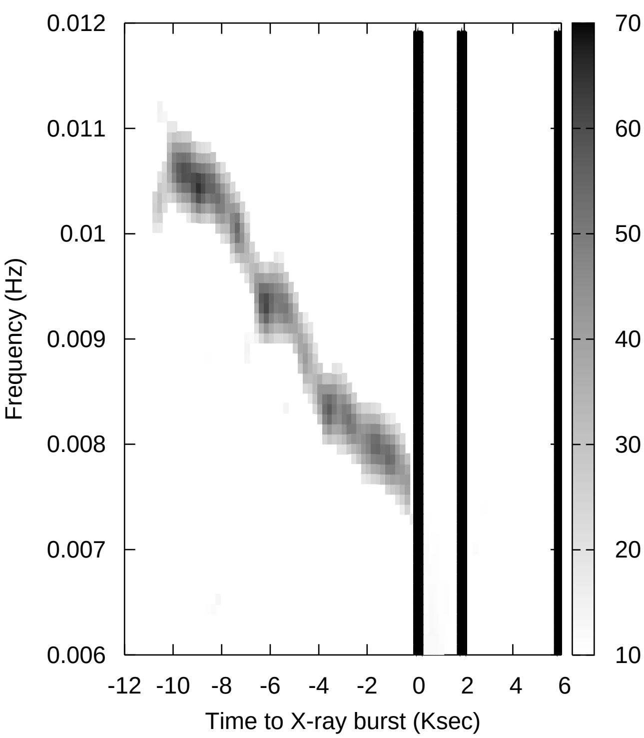

FIG. 2.— Dynamical power spectrum smoothed with a 750 seconds sliding window with steps of 200 seconds, showing the mHz QPOs during the last 12 ksec before the X-ray burst occurs. This sequence corresponds to case B in Figures 3 & 1 – ObsId: 60032-05-02-00. The three black vertical lines correspond to the times of occurrence of the X-ray bursts. For clarity, we plot only powers above 10 which correspond to $\gtrsim 2\sigma$ (single trial per 750 seconds window but normalized to the number of possible frequencies in the range 0–0.5 Hz).

Type I X-ray bursts, superbursts, burst oscillations, photospheric radius expansion, regular and irregular burst sequences (e.g. Galloway et al. 2006) and mHz QPOs. As such, it is an ideal source to understand the relation between these different observational manifestations of nuclear burning.

Recently, Shih et al. (2005) reported that 4U 1636–53 has shown a significant decrease in its persistent L_x during the years 2000 and 2001. Altamirano et al. (2007) show that during the low L_x period, 4U 1636–53 is observed in its (hard) island states. This provides an opportunity to study the mHz QPOs in harder and lower luminosity states than was possible up to now.

2. DATA ANALYSIS & RESULTS

We used data from the RXTE Proportional Counter Array and the High Energy X-ray Timing Experiment (PCA and HEXTE, respectively; for instrument information see Jahoda et al. 2006; Gruber et al. 1996). Up to June, 2006, there were 338 public pointed observations. An observation covers 1 to 5 consecutive 90-min satellite orbits. Usually, an orbit contains between 1 and 5 ksec of useful data separated by 1–4 ksec data gaps; on rare occasions the visibility windows were such that RXTE continuously observed the source for up to 27 ksec. In total there were 649 gap-free data segments of length 0.3 to 27 ksec.

We produced energy spectra for each observation using Standard data modes and fitted them in the $2-25$ keV and $20-150$ keV bands for PCA and HEXTE, respectively. The interstellar absorption N_H was fixed at 3.75×10^{21} cm^{-2} (see Schulz 1999; Fiocchi et al. 2006). We used 1-sec resolution event mode PCA light curves in the $\approx 2-5$ keV range (where the mHz QPOs are strongest) and searched for periodicities in each of the 649 segments separately using Lomb-Scargle periodograms (Lomb 1976; Scargle 1982; Press et al. 1992). Segments in which one or more Type I X-ray bursts were detected were searched for periodicities before, in between, and after the bursts. We find that the oscillations in the $\approx 2-5$ keV range are evident from the light curves (see for example figure 1 in Revnivtsev et al. 2001). The significance as estimated from our Lomb-Scargle periodograms (Press et al. 1992) confirm that the oscillations are all above the 3σ level. We estimated the uncertainties in the measured frequencies by fitting a sinusoid to 1000 sec data segments to minimize frequency-drift effects. The typical errors on the frequency are of the order of $2-6\times10^{-5}$ Hz (or $2-6\times10^{-2}$ mHz).

We detected mHz QPOs in 124 of the 649 segments. Most occur in segments with less than 4 ksec of useful data and sometimes the QPOs cover only part of a segment. Revnivtsev et al. (2001) reported the characteristics of the mHz QPOs between March 1996 and February 1999. Using the X-ray colors averaged per observation as reported by Altamirano et al. (2007), we find that their data sample the region at hard colors $\lesssim 0.7$ and soft colors $\gtrsim 1$ (see Figure 1), which represents the so called banana state (van der Klis 2006). Some of the later observations also sample the banana state. We re-analyzed all the data in this region of the color-color diagram and found results which are consistent with those reported by Revnivtsev et al. (2001): the frequency of the QPOs varies randomly between 6 and 9 mHz.

In the harder state close to the transition between the island and banana state and marked with the ellipse

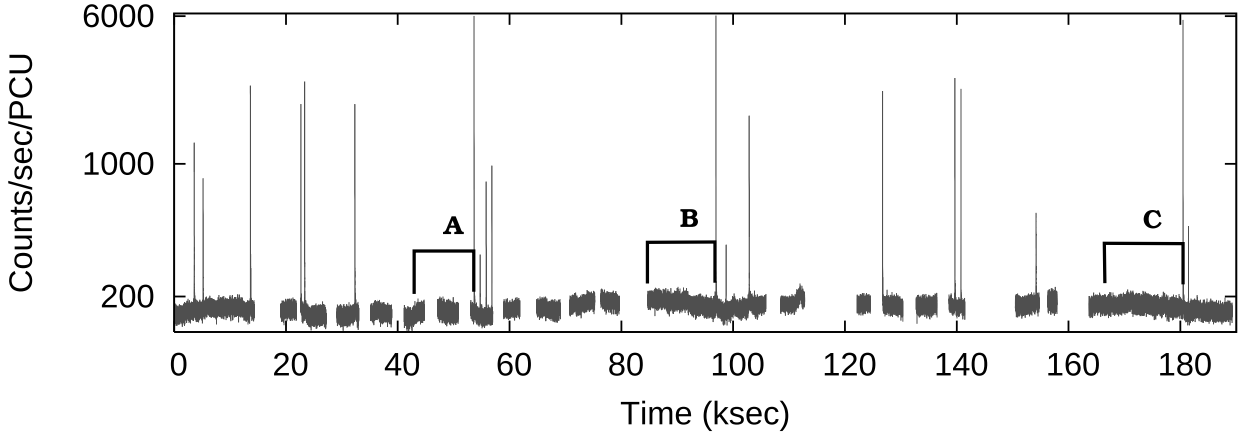

FIG. 3.— 2–60 keV PCA light curve of observations 60032-05-01,02,03 and 04. *A*, *B* and *C* indicate intervals in which the mHz QPOs are detected. In all three cases, the frequency of the mHz QPO decreases with time until the appearance of an X-ray burst.

drawn in Figure 1, we found 22 segments with significant mHz QPOs; in these observations, the (2–150 keV) luminosity was $6-10\times10^{36}(d/(6kpc))^2$ erg s^{-1}, while for the other cases, corresponding to the banana state, it was higher $(10-35\times10^{36}(d/(6kpc))^2$ erg s^{-1}).

Among the 22 segments, we distinguish two groups based on segment length: the first consisting of 4 segments each with more than 14 ksec of uninterrupted data, and the second consisting of 18 segments each corresponding to one orbit with less than ≈ 4 ksec of useful data. For all four segments in the first group, we measure a systematic decrease of frequency from between 10.7 and 12.5 mHz down to less than 9 mHz over a time interval of 8 to 12 ksec, after which an X-ray burst occurs and the QPOs disappear (the QPOs become much less than 3σ significant). Figure 2 shows a representative dynamical power spectrum corresponding to one of these segments (interval B in Figure 3). The QPO is present ≈ 12 ksec seconds before the burst and its frequency systematically decreases with time from ≈ 10.7 mHz down to ≈ 7.6 mHz. Then the X-ray burst occurs and the QPO disappears. In the second group, 16 of the 18 segments of < 4 ksec show the mHz QPO frequency to decrease either within a segment, or between 2 or 3 consecutive orbits (with 2–4 ksec data gaps in between) at rates consistent with those seen in the 4 long segments. The two remaining segments are too short and isolated to constrain the frequency drift well.

To illustrate the interplay between this very systematic behavior of the mHz QPOs and our data structure, in Figure 3 we show a representative lightcurve. A, B and C mark three intervals in which the mHz QPOs were detected and that each terminate with an X-ray burst. As can be seen, we have data in which mHz QPOs are detected and followed through consecutive segments (case A), and data in which the oscillations are detected and disappear within one segment (cases B & C). Furthermore, we have data in which the oscillations are present from the start of the observation (case B) as well as data in which the mHz QPOs appear during an observation (case A & C).

Among our 22 segments, the frequency of the oscillations varies in the range $7-14.3$ mHz with directly observed onset frequencies between 10.7 and 14.3 mHz. Interpolating through gaps, the QPOs last for 7.5 to 16 ksec. Over such intervals, the frequency is always consistent with decreasing at average rates from 0.07 to 0.15 mHz ksec^{-1}, and the frequency had always dropped to $\lesssim 9$ mHz just before an X-ray burst (as estimated from the last 750 seconds before the burst). Interestingly, this last result applies to all cases in which we detect the mHz QPOs before an X-ray burst, including the cases that occur in the banana state: it seems that independent of the spectral state of the source, no X-ray burst will occur if the mHz QPOs are present at a frequency higher than ≈ 9 mHz (bursts do occur in both states that are not preceded by detectable mHz QPOs).

No relation between the 2–60 keV count rate and frequency was found: in two of the four long segments the count rate decreased about 10% during the time the mHz QPOs were present, while in the other two cases the count rate increased by approximately the same amount. No clear relation was found between frequency range covered and duration of the oscillation; perhaps this is related to the fact that, as shown in Figure 2, the frequency does not decrease smoothly but has short periods in which it is consistent with being constant.

When 4U 1636–53 is observed close to its island–banana state transition, the mHz QPOs disappear *only* when an X-ray burst occurs. However, this is not the case for the banana state, in which we found also observations in which the oscillation disappear below detectable levels without the occurrence of an X-ray burst. The interval of time required to again detect the oscillations after a burst occurred is variable. The two extreme cases are (i) observation 60032-01-06-000 where no mHz QPOs were detected during the ≈ 15 ksec of uninterrupted data following an X-ray burst and (ii) observation 40028-01-06-00, where mHz QPOs are detected again ≈ 6000 seconds after an X-ray burst occurred. We note that in the first case, the source was close to the transition between island and banana state while in the second case, the source was in the banana state. Nevertheless, no clear relation between this waiting time and the source state (island or banana state) was found. As bursts may be missed due to data gaps, a time interval of ≈ 1000 seconds between a (missed) X-ray burst and onset of the QPOs cannot in some cases be excluded (e.g. case A in Figure 3).

3. DISCUSSION

We have shown that close to the transition between the island and the banana state 4U 1636–53 exhibits mHz QPOs whose frequency systematically decreases with time until the oscillations disappear with the occurrence of a Type I X-ray burst. The mHz QPO frequency ν constitutes the first identified observable that can be used to predict the occurrence of X-ray bursts: when $\nu \gtrsim 9$ mHz no bursts occur, while $\nu \lesssim 9$ mHz does allow the occurrence of bursts. If a systematic frequency drift occurs, then a burst happens within a few kilo-seconds after ν drops below 9 mHz. This observational result confirms that the mHz QPO phenomenon is intimately related with the processes that lead to a thermonuclear burst.

The fact that the observation of a systematic frequency decrease with time implies the occurrence of a future X-ray burst, strongly suggests that the frequency of the mHz QPOs is related to the burning processes on the neutron star surface. One possibility is that the frequency of the QPO is somehow a measurement of the accumulation of fresh fuel on the neutron star surface which will be available for a future thermonuclear burst. To our knowledge, there has been only one attempt to theoretically explain the mHz QPOs phenomena (Heger et al. 2007). In this model the frequency of the QPO depends, among others, on the amount of available fresh fuel, on the local accretion rate and the composition of the material. It is beyond the scope of this Letter to perform numerical simulations as those reported by Heger et al. (2007). In the rest of this discussion we briefly compare these authors' model predictions with our observations and propose some more complex scenarios.

Analytical and numerical results based on the simplified one-zone model of Paczynski (1983) in the Heger et al. (2007) marginally stable burning model (see Section 1) predict that (i) close to the boundary between stable and unstable burning, the NS surface will show temperature fluctuations with constant frequency ν if the local accretion rate $\dot{m}$ remains constant; (ii) this marginally stable burning regime will occur at $\dot{m}$ near Eddington, hence accretion must be confined to a surface area S_A that is much smaller that the total area of the NS; (iii) ν correlates with $\dot{m}$ (see figure 4 in Heger et al. 2007) and (iv) thermonuclear bursts and mHz QPOs should not be observed at the same luminosity and therefore presumably at the same $\dot{m}$.

In this paper, we show that for constant luminosity the QPO frequency can systematically decrease in time and that instantaneously measured frequencies can be the same for different luminosities. We also show that mHz QPOs and thermonuclear bursts do in fact occur at the same luminosity and that both phenomena are clearly related. This means that we are dealing with a more complex scenario than that introduced by Heger et al. (2007).

The amount of time between the preceding X-ray burst and the onset of mHz QPOs is variable ($>$ 6ksec) and apparently independent of source state. If the system is locally accreting at $\dot{m} \simeq \dot{m}_{Edd}$ and if none of the accreting fuel is burnt, only $\approx$ 1000 seconds are required to accrete a fuel layer of column depth y_f capable of undergoing marginally stable burning ($y_f \approx 10^8$ g cm^{-2} and $\dot{m} \approx 8 \cdot 10^4$ g cm^{-2} s^{-1} – see e.g. Heger et al. 2007). One possible explanation for the observed longer intervals between burst and onset of oscillations, is that a large fraction of the accreted fuel is burnt as it is accreted on the neutron star surface. Of course the burning fraction could vary in time, and this estimate is assuming that all the fuel was burnt during the last X-ray burst, which is not always true (Bildsten 1998). Interestingly, if this interpretation is correct and low partial burning fractions can occur, under certain conditions the mHz QPOs could appear in much less than a 1000 seconds after an X-ray burst.

The fact that the amount of time between the preceding X-ray burst and the onset of mHz QPOs is variable may be also an indication that not all the accreted fuel is burnt nor available to participate in the marginally stable burning. For example, accretion could occur onto an equatorial region occupying less than 10% of the surface area of the star (Heger et al. 2007). A possibility is that part of the fresh fuel burns stably at a rate $B(t)$ per unit area while the other part leaks away from this region at a rate $R(t)$. While the material accumulated at a rate $R(t)$ would serve as fuel for a thermonuclear burst, marginally stably burning of the matter on the equatorial belt is (in principle) still possible. Although such scenario cannot explain the frequency drifts we observe, it can explain why mHz QPO and X-ray bursts do occur at the same $\dot{m}$. If mHz QPOs can only occur at a certain local accretion rate $\dot{m}$ ($\simeq \dot{m}_{Edd}$), a small change in effective local accretion rate will lead to an absence of mHz QPOs. This might explain why the mHz QPOs are not always present between X-ray bursts.

Another possibility (which is not taken into account in Heger et al. (2007)'s model) is that there is a significant heat flux from deeper in the star that heats the region undergoing marginally stable burning. For example, changes in heat flux due to energy that is first conducted into deeper layers during an X-ray burst and then slowly outwards towards the surface might be possible. Such a change in the heat flux could affect the conditions of the burning layer (e.g. temperature or burning rate $B(t)$) and therefore could affect the characteristics of the burning processes on the neutron star surface.

Other aspects of the observations offer further challenges for theoretical models that explain burning processes on the neutron star surface as well those which explain atoll sources states. In particular, (i) why the systematic frequency drifts are observed close to the transition between the island and the banana state while the frequencies are approximately constant in the banana state. This may be another indication that the disk geometry of the system is changing during the state transition (see e.g. Gierliński & Done 2002); (ii) why in the transition between island and banana state the oscillations disappear *only* when an X-ray burst occurs, while in the banana state they can also disappear without an X-ray burst (see Section 2). Clearly, further theoretical work is needed. More observational work on the interactions between mHz QPOs and X-ray bursts is in progress and will provide further clues for theoretical models.

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